

## Comparison between ATSR-2 stereo, MOS O<sub>2</sub>-A band and ground-based cloud top heights

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A new method to retrieve cloud top heights stereoscopically using the dual-view facility of the Along Track Scanning Radiometer 2 (ATSR-2) instrument is assessed. This assessment is performed through a comparison of the cloud top heights obtained from ATSR-2 stereo and those derived from a 94-GHz radar, radiosonde profiles and independently from the Modular Optoelectronic Scanner (MOS) using the O<sub>2</sub>-A band. The data for this study were collected over the United Kingdom from September 1998–March 1999. The results show that the accuracy of the ATSR-2 stereo heights is generally as predicted on theoretical grounds, with the errors in the 1.6  $\mu\text{m}$  and 0.65  $\mu\text{m}$  stereo heights rarely exceeding 2 km. Case study periods with disagreements between the ATSR-2 heights and the ground-based retrievals are often due to the lack of precise match-ups between the ground-based and satellite scenes, while the MOS O<sub>2</sub>-A band is shown sometimes to miss the tops of high clouds. Evidence that the 11  $\mu\text{m}$  channel is more sensitive to high clouds than originally thought is given and a future application of multi-spectral stereo cloud top heights is proposed.

### 1. Introduction

The impact of clouds on the Earth's radiative balance has long been recognised as a major issue in climate and weather forecasting studies (e.g., Ramanathan *et al.* 1989). Depending on their composition and height, clouds may have either a

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warming or a cooling effect (Hartmann *et al.* 1992). In order to assess the overall effect of a cloud on the Earth's radiative balance, one must be able to assign precisely an average cloud top height (CTH) to the cloud layer. Otherwise, determining the temperature and composition (in terms of ice or liquid water) of the cloud layer, which are principal factors in cloud forcing, is not possible. Only satellite-based sensors with their global coverage are able to characterise cloud top heights on a scale sufficient for comprehensive climate and weather forecasting studies.

The Along Track Scanning Radiometer 2 (ATSR-2) is a dual-view scanning radiometer that was launched in 1995. The ATSR-2 observes the Earth with 7 channels across the visible, near-infrared and thermal infrared regions of the electromagnetic spectrum. The unique dual-view feature of ATSR-2 allows the application of stereo-photogrammetric techniques to retrieve information on cloud top height (e.g., Lorenz 1985, Harris 1993). Other techniques in current use, such as the CO<sub>2</sub> slicing method (e.g., Menzel 1983), the water vapour technique (Szejwach 1982) and the O<sub>2</sub>-A band technique (Fischer and Grassl 1991, Preusker *et al.* 2007), are spectrally-based and often require ancillary information in their retrieval of cloud top height. For example, the CO<sub>2</sub>-slicing and water vapour techniques require external information on the local atmospheric profiles of temperature, pressure and/or humidity, while the O<sub>2</sub>-A band technique requires surface reflectivity data to identify thin clouds over land. Stereo matching has the advantage of being a stand-alone technique based only on geometric considerations and has already been applied successfully to cloud top height retrievals (e.g., Prata and Turner 1997).

A new stereo matching technique and associated processing chain, collectively called M4 (Muller *et al.* and Denis *et al.* 2007), have been applied to the 0.65, 1.6 and 11  $\mu\text{m}$  channels of ATSR-2 in order to retrieve cloud top heights for scenes over the United Kingdom from September 1998 through March 1999. In their description of the M4 algorithm, Muller *et al.* (2007) estimated that the theoretical expected accuracy of the method is 1 km. The objective of this paper is to assess the accuracy of the Muller *et al.* (2007) technique by comparing the cloud top heights (CTHs) it retrieves to ground-based measurements obtained with a 94-GHz radar situated at Chilbolton (51.14° N, 1.44° W) and with radiosondes (RS) launched from the Aberporth (52.13° N, 4.57° W) and Hemsby (52.68° N, 1.68° E) stations. As these ground-based and in-situ measurements provide a full profile of information from the surface to the tropopause and allow the possibility of identifying multi-layered clouds, we compared the ATSR-2 stereo-derived cloud top heights with the tops of the highest cloud layers detected by the ground-based instruments. It is not possible to give an absolute accuracy for the heights retrieved with these instruments, but independent comparisons with lidar retrievals have shown that cloud heights retrieved from radar agreed with the lidar measurements within 125 m at cloud base (Clothiaux *et al.* 1998) and the two radiosonde techniques used here have been shown to give cloud top heights  $350\text{ m} \pm 750\text{ m}$  higher than the radar cloud top heights retrieved at the Atmospheric Radiation Measurements (ARM) Program Southern Great Plains site (Naud *et al.* 2003). In a few cases, retrievals of cloud top pressure (CTP) derived from the Modular Optoelectronic Scanner (MOS; Zimmermann and Neumann, 1997) O<sub>2</sub>-A band (Preusker *et al.* 2007) onboard IRS-P3 were coincident with the ATSR-2 measurements, so we compared the two sets of retrieved cloud top heights. The accuracy of MOS O<sub>2</sub>-A band CTP has been shown to be about 30 hPa for clouds with an optical depth of 5 at 550 nm (i.e. less

than 500 m error in CTH for a standard mid-latitude winter atmosphere), but there is no reliable estimate available for clouds with optical depths less than 5 (Preusker *et al.* 2007).

This paper is divided into five sections apart from the introduction. We begin the analysis in §2 with comparisons between ATSR-2 and 94-GHz radar cloud top heights, while §3 shows comparisons between ATSR-2 and radiosonde-derived cloud top heights. In §4 we compare both ATSR-2 and ground-based cloud top heights with MOS cloud top pressure and in §5 we extend the ATSR-2 and MOS comparisons over the British Isles. Discussion of the results and our final conclusions are presented in §6.

## 2. Comparison between ATSR-2 stereo and 94-GHz radar-derived CTH over Chilbolton

Out of the 27 dates when ATSR-2 stereo height retrievals over Chilbolton were possible, 11 scenes (Table 1) were deemed suitable for comparison with the ground-based radar data. We processed the 94-GHz data using an algorithm that was originally implemented and tested at the ARM Southern Great Plains site (Clothiaux *et al.* 2000) and subsequently adapted to take advantage of the processing enhancements developed at the University of Reading specifically for the Chilbolton 94-GHz cloud radar. This algorithm provides a reflectivity clutter flag product that indicates, as a function of time and height, clear, cloudy, a mixture of cloud and clutter or clutter only contributions to the radar returns from each resolution volume. The clutter may be insects, vegetation, or any other non-hydrometeor particles.

We extracted the median, mean and maximum cloud top height contained in the radar mask over a time interval centred on the nadir ATSR-2 scan of the Chilbolton site. The minimum time interval for the radar data sampling has to include the time it takes from the forward to the nadir view over Chilbolton, which we estimated to be about 195 s. We tested various time durations for the comparison from 200 s to 7200 s and found that a  $\pm 320$  s time interval was the most reliable one for picking up clouds in broken cloud or strong wind conditions for all the cases analysed here. We computed the median and mean radar CTH over the time interval for those clouds detected by the radar and calculated the fraction of this interval to the total sampling time period. The median CTH was used for the comparison, but for some cases the maximum value gave a more consistent comparison with the ATSR-2 stereo-derived heights in scattered cloud conditions. In the comparisons with the 94-GHz radar-derived cloud top heights the ATSR-2 stereo heights are selected over a  $\pm 0.02^\circ$  latitude-longitude box centred on Chilbolton and the spatial mean, median and standard deviation are calculated. The use of a latitude-longitude box around the ground-based station overcomes the potential ATSR-2 geolocation problems, so that if the clouds are uniform, the pixels shift has no impact, if the clouds are broken and sparse, they are potentially still within the box.

A summary of the median ATSR-2 stereo and radar CTHs, with corresponding standard deviations, for the 11 dates from 11 November 1998–11 February 1999 is presented in table 1. In figure 1, the ATSR-2 stereo median CTHs that were derived from the ATSR-2  $0.65\ \mu\text{m}$ ,  $1.6\ \mu\text{m}$  and  $11\ \mu\text{m}$  channels are plotted against the radar median cloud top heights over the observational time period. On three occasions (24 November 1998, 3 December 1998 and 7 January 1999) all three ATSR-2 channels detected a cloud at the same level as detected by the radar. For another three scenes

Table 1. ATSR-2 11  $\mu\text{m}$ , 1.6  $\mu\text{m}$  and 0.65  $\mu\text{m}$  channel stereo, together with MOS and 94-GHz radar, median CTHs and standard deviations centred on Chilbolton. The ATSR-2 and MOS CTHs were averaged over a  $\pm 0.02^\circ$  latitude-longitude box around Chilbolton. The radar data have been processed using the algorithm from Clothiaux *et al.* (2000) and the radar-derived cloud top heights correspond to the median height detected over a time period equivalent to twice the time it takes from the forward ATSR-2 view of Chilbolton to the nadir ATSR-2 view of Chilbolton, centred on the nadir ATSR-2 view start-time. The cloud conditions are derived from the radar profiles to decide if the situation is single or multiple layers, and from ATSR-2 CTHs distributions within the latitude-longitude box to decide if the highest layer is scattered or overcast.

Date	Cloud condition	ATSR-2-11 $\mu\text{m}$ median CTH (km)	ATSR-2-1.6 $\mu\text{m}$ median CTH (km)	ATSR-2-0.65 $\mu\text{m}$ median CTH (km)	MOS median CTH (km)	CRF radar median CTH (km)	Comments
24 November 1998	Thick single layer	$9.8 \pm 0.0$	$9.8 \pm 1.8$	$9.8 \pm 0.0$		$8.3 \pm 0.1$	Three ATSR-2
3 December 1998	Single low cloud	$2.2 \pm 0.0$	$2.2 \pm 8.4$	$2.2 \pm 0.0$		$1.2 \pm 0.1$	channels and radar
7 November 1999	Thick single high cloud	$8.9 \pm 0.7$	$8.9 \pm 0.4$	$9.6 \pm 0.7$		$7.7 \pm 0.2$	detect same layer
11 November 1998	Mid-level, scattered	$10.3 \pm 0.2$	$6.2 \pm 1.6$	$6.2 \pm 2.0$	$4.5 \pm 0.2$	$6.3 \pm 0.3$	Two ATSR-2
27 November 1998	2 layers	$2.8 \pm 0.4$	$4.9 \pm 0.2$	$4.9 \pm 0.0$		$5.3 \pm 0.1$	channels agree with
2 February 1999	Scattered high	$9.0 \pm 0.0$	$1.5 \pm 5.4$	$8.3 \pm 5.7$		$7.2 \pm 0.2$	radar
20 January 1999	2 layers, scattered high	$9.6 \pm 1.1$	$16.5 \pm 3.7$	$15.8 \pm 5.2$		$5.6 \pm 1.2$	Max radar CTH
23 January 1999	Scattered high over low	$10.6 \pm 0.0$	$11.3 \pm 2.2$	$10.6 \pm 3.9$		$1.0 \pm 3.0$	agree with at least one ATSR-2 channel
10 December 1998	Low to mid level layer	$4.1 \pm 0.4$	$4.1 \pm 0.0$	$4.1 \pm 3.9$		$1.3 \pm 0.0$	ATSR-2 CTHs > radar CTH
11 February 1999	Multilayer	$3.0 \pm 0.0$	$3.7 \pm 0.0$	$3.0 \pm 0.0$		$8.5 \pm 0.5$	ATSR-2 CTHs < radar CTH
17 November 1998	High cloud	$8.7 \pm 0.3$	$11.1 \pm 0.4$	$8.7 \pm 0.4$		$0.0 \pm 0.0$	False positive

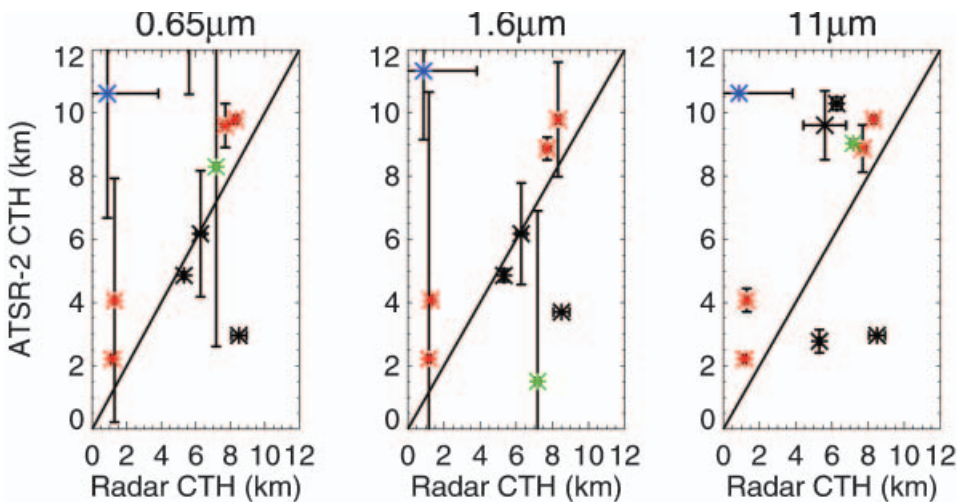


Figure 1. Comparison between ATSR-2 stereo and radar median CTHs over Chilbolton. The vertical lines correspond to  $\pm$  one standard deviation calculated for the ATSR-2 latitude-longitude box centred at Chilbolton and provide information on how much ATSR-2 CTH varied in the vicinity of the radar and how broken the highest clouds were. Black shows multilayer with highest layer scattered, red shows single overcast clouds, blue shows multilayer with highest layer overcast and green shows single scattered clouds.

one ATSR-2 channel retrieval disagreed with the other two ATSR-2 channel retrievals as well as the radar-derived median CTHs. For 2 scenes (20 January 1999 and 23 January 1999), the radar median CTH was much lower than the three ATSR-2 CTHs, but the radar maximum CTH agreed with at least one of the ATSR-2 channel CTHs. These scenes were similar in that they contained high scattered clouds over a lower cloud layer as illustrated on the radar reflectivity plot. On one occasion (10 December 1998) the radar CTH indicated a low single cloud layer whereas the three ATSR-2 channels agreed on the presence of a mid-level cloud. The radar reflectivity plot showed that the cloud vertical extent was increasing during and after the ATSR-2 overpass, suggesting that the area observed by ATSR-2 may have been covered with the higher part of the cloud system whereas the part that predominantly travelled over the radar during the observational time period was lower. Another case (11 February 1999) showed a multilayer scene and the three ATSR-2 CTHs referred to the top of the layer below the highest one detected by the radar. Finally, on one occasion (17 November 1998) the three ATSR-2 channels detected a high cloud that the radar did not detect and a longer sampling period did not show any cloud in the radar reflectivity plots. One cause of this problem may be that these high clouds detected by ATSR-2 were composed of particles too small to be detected by the radar.

Removing the last three case study periods mentioned above from the data pool (10 December 1998, 2 November 1999 and 17 November 1998), we were left with 8 cases when ATSR-2 stereo and radar-derived median CTHs could be compared (using radar maximum CTH when appropriate). On five of these occasions, the ATSR-2 0.65 μm channel retrieved higher CTHs than the radar. For four of these cases both instruments detected a high CTH and one case only showed a low cloud layer. On two of the remaining occasions, the ATSR-2 0.65 μm channel CTH was lower than the radar CTH and for both cases the cloud was at mid-level (between 3

and 7 km). Finally, on 20 January 1999 the ATSR-2 0.65  $\mu\text{m}$  channel CTH was far too high for a mid-latitude winter cirrus, which means that the stereo height estimate could be affected by blunders. These blunders occur sometimes, but not usually for more than 1% of all pixels matched (Muller *et al.* 2007). Overall, the difference between the radar and ATSR-2 0.65  $\mu\text{m}$  derived CTHs varied between  $-1.9$  and  $0.4$  km with an average difference of  $-0.9$  km and a standard deviation of  $0.8$  km.

For the same 8 cases above the ATSR-2 1.6  $\mu\text{m}$  channel CTH was lower than the radar CTH on 3 occasions, but for two of these cases the height differences were less than  $1.5$  km of altitude (same mid-level cloud cases as for the ATSR-2 0.65  $\mu\text{m}$  channel). For the third case (2 February 1999) the ATSR-2 1.6  $\mu\text{m}$  channel failed to detect the highest cloud layer, reporting instead the CTH of a lower level cloud layer. Nevertheless, a histogram of all ATSR-2 1.6  $\mu\text{m}$  channel CTHs selected in the  $0.02^\circ$  latitude-longitude box showed that the high cloud was in fact detected, but only over a limited area. For the remaining four dates the ATSR-2 1.6  $\mu\text{m}$  channel CTH was always higher than the radar CTH. Of these four cases, high cloud layers were detected on three occasions and the difference could be due to insufficient radar sensitivity to detect the top of these clouds. The low cloud case (3 December 1998) only shows a difference of  $1$  km. Similar to the ATSR-2 0.65  $\mu\text{m}$  channel CTHs on 20 January 1999, the ATSR-2 1.6  $\mu\text{m}$  channel CTHs were far too high for a mid-latitude winter cirrus and again this is probably caused by blunders. Overall, the difference between the radar and ATSR-2 1.6  $\mu\text{m}$  channel CTHs for 7 of these cases was between  $-1.7$  km and  $5.7$  km, giving an average difference of  $0.1$  km and a standard deviation of  $2.6$  km. If we remove the 2 February 1999 case from the pool, the average becomes  $-0.8$  km with a standard deviation of  $0.9$  km.

The ATSR-2 11  $\mu\text{m}$  channel CTH was lower than the radar CTH on one occasion only out of the 8 scenes when a comparison was possible, this case being 27 November 1998 when the highest layer was missed by the ATSR-2 11  $\mu\text{m}$  channel stereo CTH retrieval. At 11  $\mu\text{m}$  the contrast between the nadir and forward views when low clouds are present may not be enough for the stereo matcher to perform accurately. For the remaining seven cases the ATSR-2 11  $\mu\text{m}$  channel reported higher cloud top heights than the radar, most of the heights being above  $7$  km, except for the 3 December 1998 case, where a low cloud was present and the difference was only  $1$  km. For these 8 cases the difference between the radar and ATSR-2 11  $\mu\text{m}$  channel CTHs varied between  $-4$  km and  $2.5$  km with an average of  $-1.1$  km and a standard deviation of  $1.8$  km. Presumably, the sensitivity of the ATSR-2 11  $\mu\text{m}$  channel to the highest levels within a high cloud layer must have been greater than the sensitivity of the radar to the particles at these altitudes.

Overall, the agreement between ATSR-2 stereo and 94-GHz radar CTH was generally within  $2$  km, but there was a tendency for the radar to underestimate CTH for high clouds. This is for two main reasons. Firstly the minimum detectable signal increases with range from the radar, from around  $-51$  dBZ at  $1$  km to  $-31$  dBZ at  $10$  km (taking into account the two-way attenuation by water vapour and oxygen in the lower atmosphere of  $1$ - $2$  dB). Secondly ice clouds of a given optical depth tend to contain smaller particles at higher altitudes, making them more difficult to detect using radar. The presence of low-level liquid water clouds can cause an additional uncertain attenuation, although the attenuation by ice clouds is very small in comparison. The ability of the Chilbolton 94 GHz radar to detect ice clouds at different heights was discussed further by Hogan *et al.* (2001).

### 3. Comparison between ATSR-2 stereo and radiosonde-derived CTH over Hemsby and Aberporth

We used two techniques to retrieve cloud boundaries from radiosonde profiles. One technique was based on relative humidity thresholds (Wang and Rossow 1995; hereafter WR95), while the second method was based on the sign of the second derivatives of humidity and temperature profiles together with a threshold on dew point depression (Chernykh and Eskridge 1996, hereafter CE96). In this second approach two different thresholds on cloud amount were tested, an 80% threshold applying when the cloud amount must be at least 80% for a layer to be considered cloudy and a 60% threshold holding when the cloud amount was at least 60% in a cloudy layer (CE96). When no distinction between the WR95 and CE96 methods is necessary, we refer to them both as the radiosonde (RS) techniques.

We compared radiosonde-derived CTH of the highest detected cloud with those derived from ATSR-2 from August 1998 through March 1999. During this time period, high-resolution (i.e. 2 s) radiosonde data were coincident with interesting ATSR-2 overpasses 17 times at Aberporth and 5 times at Hemsby. As for the radar comparisons, the ATSR-2 CTHs were derived by averaging all CTHs within a  $\pm 0.02^\circ$  latitude-longitude box centred at the relevant radiosonde launch site. Unfortunately, latitude and longitude information were not provided by the radiosondes during ascent, preventing us from precisely aligning radiosonde measurements with ATSR-2 pixels. In order to overcome this problem larger latitude-longitude boxes were used to sample ATSR-2 CTHs and assess their frequency of occurrence.

Results of comparisons between CTH derived from the three ATSR-2 channels using stereo and CTH obtained by applying the WR95 and CE96 techniques to radiosonde data are illustrated in figure 2 and summarized in table 2. The top row in figure 2 shows results for WR95, while the bottom row in figure 2 shows results from CE96. Wang *et al.* (1999) demonstrated that layers close to the surface with high humidity levels are sometimes cloud free. As both the WR95 and CE96 methods use thresholds on humidity to select cloud layers, they both have the potential to specify clouds near the surface during clear-sky periods. In their original work WR95 suggested that all cloud layers with a top below 500 m should not be considered as cloudy and we have followed their rule. Consequently, for the RS techniques we considered a case to be clear if the RS technique gave a cloud top height less than 0.5 km, while for the ATSR-2 stereo CTH we considered an area to be free of cloud if the retrieved height was less than 0.7 km.

Considering both the Aberporth and Hemsby stations, there was a pool of 22 radiosonde profiles coincident with ATSR-2 overpasses for which we compared cloud retrievals. Of these 22 profiles 5 cases were indicated clear by the radiosondes but only 1 of these 5 cases was indicated as clear by the three ATSR-2 channel retrievals. The other four cases contained scattered clouds that were not systematically detected by all three ATSR-2 channels. The RS did not detect these clouds in these 4 cases either because the sonde travelled between broken clouds or the clouds were too dry for the thresholds on humidity used by both methods.

For the remaining 17 cases, which were cloudy, CTHs were categorised according to a high ( $\text{CTH} > 7 \text{ km}$ ), mid-level ( $3 < \text{CTH} \leq 7 \text{ km}$ ) and low ( $\text{CTH} \leq 3 \text{ km}$ ) cloud classification. For 6 cases the three ATSR-2 channel retrievals agreed on the cloud top level, following the high-mid-low classification, and they also agreed with at least one of the RS CTHs. For 5 of these 6 cases the clouds were high with a CTH

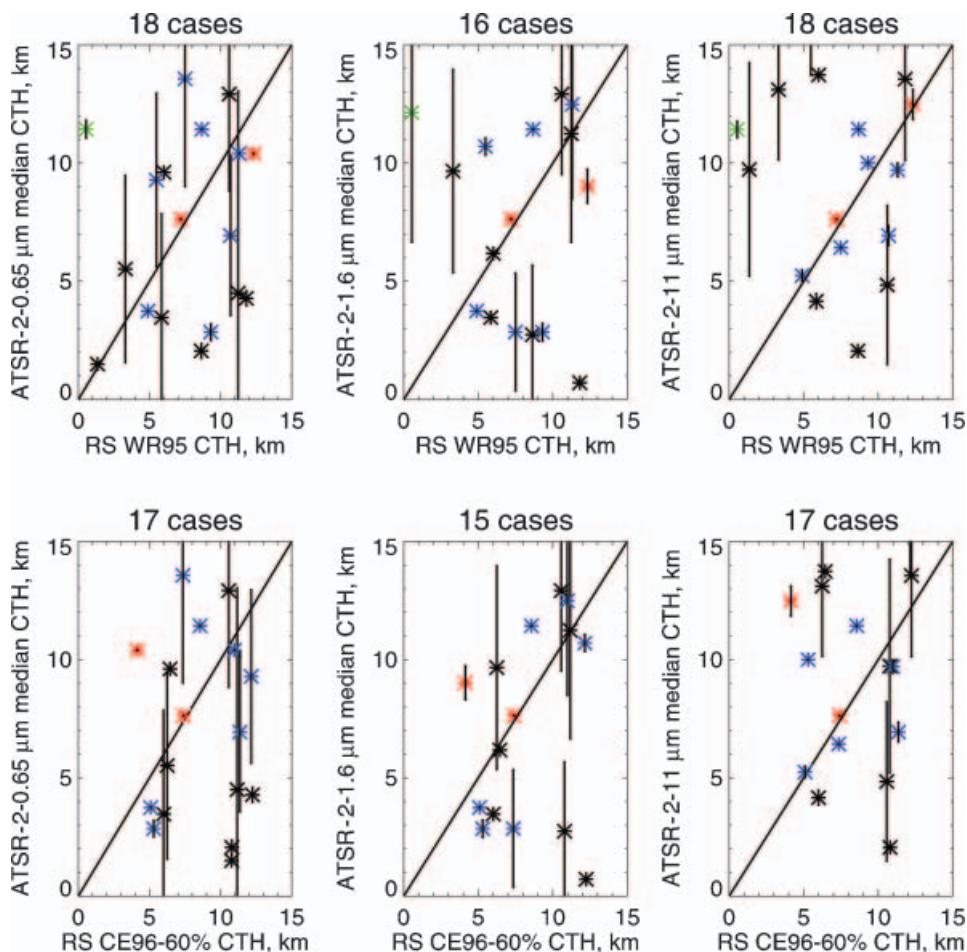


Figure 2. Comparison between the ATSR-2 0.65  $\mu\text{m}$ , 1.6  $\mu\text{m}$  and 11  $\mu\text{m}$  channel stereo CTHs and WR95 CTHs (top panel) and CE96-60% CTHs (lower panel) for Hemsby and Aberporth. The vertical lines correspond to  $\pm$  one standard deviation calculated for the latitude-longitude box centred on the radiosonde stations and provide information on how much ATSR-2 CTH varied in the vicinity of each site and how broken the highest clouds were. Black shows multilayer with highest layer scattered, red shows single overcast clouds, blue shows multilayer with highest layer overcast and green shows single scattered clouds.

above 7 km. The largest difference between the ATSR-2 and RS CTHs was found on 7 January 1999 when the ATSR-2 CTHs were more than 2 km above the RS CTHs. For 8 cases there was at least one ATSR-2 CTH that agreed with at least one RS CTH. All these cases contained more than one cloud layer in the RS profile. Out of these 8 cases ATSR-2 11  $\mu\text{m}$  channel CTHs were close to RS CTHs in 4 cases, were higher than RS CTHs in 3 cases and were below the highest layer detected by RS in one case. The ATSR-2 1.6  $\mu\text{m}$  channel CTHs agreed with RS CTHs for 3 cases, referred to the top of a lower layer in 2 cases, did not detect a cloud at all in 2 cases, and referred to a cloud above the highest RS cloud for one occasion. The ATSR-2 0.65  $\mu\text{m}$  channel CTHs agreed with RS CTHs for 2 cases, were well above the RS CTHs for two occasions and referred to the top of a lower layer for 4 occasions.

Table 2. ATSR-2  $11\ \mu\text{m}$ ,  $1.6\ \mu\text{m}$  and  $0.65\ \mu\text{m}$  channel stereo, together with MOS, CE96-80%, CE96-60% and WR95, median CTHs and standard deviations over Aberporth and Hemsby. The ATSR-2 and MOS CTHs are selected within  $\pm 0.02^\circ$  latitude-longitude centred on the radiosonde stations. The cloud conditions are derived from the RS cloud boundary retrieval to decide if the situation is single or multiple layers, and from ATSR-2 CTHs distributions within the latitude-longitude box to decide if the highest layer is scattered or overcast.

Date	Cloud condition	$11\ \mu\text{m}$ ATSR-2 median CTH (km)	$1.6\ \mu\text{m}$ ATSR-2 median CTH (km)	$0.65\ \mu\text{m}$ ATSR-2 median CTH (km)	MOS CTH median (km)	CE96-80% CTH (km)	CE96-60% CTH (km)	WR95 CTH (km)	Comments
8 September 1998	Low, scattered	$2.1 \pm 0.6$	$1.4 \pm 0.4$	$1.4 \pm 0.0$		0.00	0.00	0.00	False positive
1 January 1999	High scattered clouds	$11.4 \pm 0.3$	$12.1 \pm 5.5$	$11.4 \pm 0.4$		0.0	0.4	0.5	
10 January 1999	Clear, scattered clouds	$0.7 \pm 0.0$	$0.7 \pm 0.0$	$11.0 \pm 3.6$		0.0	0.0	0.0	
14 January 1999	Clear, scattered clouds	$0.7 \pm 0.0$	$1.4 \pm 3.4$	$4.1 \pm 0.0$	$1.8 \pm 0.6$	0.0	0.0	0.0	
17 January 1999	Clear	$0.7 \pm 0.0$	$0.7 \pm 0.0$	$0.0 \pm 0.0$		0.0	0.0	0.0	All clear
20 August 1998	Multilayer, overcast	$17.8 \pm 4.1$	$10.7 \pm 0.4$	$9.3 \pm 3.7$		0.9	12.2	5.5	Cloudy: All 3 ATSR-2 channels agree with 1 RS
7 January 1999	Multilayer, overcast	$11.4 \pm 0.0$	$11.4 \pm 0.0$	$11.4 \pm 0.0$		8.4	8.6	8.7	
26 January 1999	Single layer, overcast	$7.6 \pm 0.0$	$7.6 \pm 0.0$	$7.6 \pm 0.0$		7.2	7.4	7.2	
2 March 1999	Single layer, overcast	$12.5 \pm 0.6$	$9.0 \pm 0.7$	$10.4 \pm 0.0$	$4.9 \pm 0.2$	11.9	12.0	12.3	
17 November 1998	Multilayer, overcast	$9.7 \pm 0.3$	$12.5 \pm 4.0$	$10.4 \pm 0.0$		10.5	10.9	11.3	
27 February 1999	Multilayer, overcast	$5.2 \pm 0.2$	$3.7 \pm 0.0$	$3.7 \pm 0.0$		4.0	5.1	4.9	
29 October 1998	Multilayer, overcast	$10.0 \pm 0.0$	$2.9 \pm 0.4$	$2.9 \pm 0.4$		8.7	9.2	9.3	At least one ATSR-2 channel agrees with one RS
29 December 1998	Multilayer, scattered	$13.7 \pm 0.0$	$6.2 \pm 0.0$	$9.6 \pm 0.3$		6.1	6.5	6.0	
23 January 1999	Multilayer, scattered	$17.3 \pm 0.7$	$11.2 \pm 4.6$	$4.5 \pm 8.6$	$7.3 \pm 0.1$	10.6	11.2	11.2	
11 February 1999	Multilayer, scattered	$13.6 \pm 3.4$	$0.7 \pm 0.0$	$4.3 \pm 0.3$	$3.9 \pm 0.0$	3.4	12.3	11.8	
3 December 1998	Multilayer, overcast	$6.4 \pm 0.0$	$2.9 \pm 2.5$	$13.6 \pm 4.6$		0.00	7.4	7.5	
8 February 1999	Multilayer, scattered	$4.9 \pm 3.4$	$12.9 \pm 3.4$	$12.9 \pm 4.1$		9.5	10.6	10.6	
5 September 1998	Multilayer, scattered	$9.7 \pm 4.5$	$0.00 \pm 0.0$	$1.5 \pm 0.0$		0.00	10.8	1.4	
10 December 1998	Multilayer, scattered	$13.1 \pm 3.0$	$9.7 \pm 4.3$	$5.5 \pm 4.0$		0.1	6.2	3.3	

Table 2. (Continued).

Date	Cloud condition	11 $\mu\text{m}$ ATSR-2 median CTH (km)	1.6 $\mu\text{m}$ ATSR-2 median CTH (km)	0.65 $\mu\text{m}$ ATSR-2 median CTH (km)	MOS CTH median (km)	CE96-80% CTH (km)	CE96-60% CTH (km)	WR95 CTH (km)	Comments
1 November 1998	Multilayer, scattered	$2.1 \pm 0.0$	$2.7 \pm 2.9$	$2.1 \pm 0.3$		8.2	10.8	8.6	All ATSR-2
13 October 1998	Multilayer, scattered	$4.2 \pm 0.3$	$3.5 \pm 0.2$	$3.5 \pm 4.4$		1.2	6.00	5.8	CTH < RS CTH
22 December 1998	Multilayer, overcast	$6.9 \pm 0.4$	$0.7 \pm 2.2$	$6.9 \pm 3.4$		0.2	11.4	10.7	ATSR-2 CTHs lower than RS

For 2 of the 17 cloudy scenes (13 October 1998 and 1 November 1998) the three ATSR-2 channel retrievals yielded CTHs close to each other but between lower cloud layers detected by the RS methods. These results could be from a collocation problem as the RS may detect clouds beyond the latitude-longitude limits set for the selection of ATSR-2 CTHs. The remaining scene (22 December 1998) shows good agreement between ATSR-2 11  $\mu\text{m}$  and 0.65  $\mu\text{m}$  channel CTHs, although the CTHs correspond to a lower layer than the highest one detected by the RS methods, whilst the ATSR-2 1.6  $\mu\text{m}$  channel failed to detect a cloud. The highest RS layer may be either too optically thin for all 3 ATSR-2 channels to detect, outside of the ATSR-2 latitude-longitude box or a moist cloud-free layer.

Reviewing the discrepancies discussed above, some are no doubt a result of the RS techniques ascribing cloud to a cloud-free moist layer or failing to properly identify cloud in a dry layer. We noticed that the ATSR-2 11  $\mu\text{m}$  channel tended to detect higher clouds when the other techniques either detected a lower altitude cloud or no cloud at all. These anomalous high cloud detections by the ATSR-2 11  $\mu\text{m}$  channel could be again the result of blunders, as mentioned in §2, or due to high thin cloud which the other two channels did not detect. The RS CTHs were in best agreement with the ATSR-2 11  $\mu\text{m}$  channel CTH retrievals with 9 cloudy scenes out of 17 having differences within 2 km. Relative to the RS CTHs, the ATSR-2 0.65  $\mu\text{m}$  channel tended to underestimate CTH and the ATSR-2 1.6  $\mu\text{m}$  channel tended to miss clouds. Overall, for 9 of the 22 cases when all techniques detected cloud the cloud top height differences between the different techniques were within 2 km.

For all three channels the agreement was on average better when compared to the CE96-60% CTHs. Removing cases when there were known problems from the data pool, we found an average difference between RS CE96-60% CTHs and (a) ATSR-2 11  $\mu\text{m}$  channel CTHs of  $-0.3\text{ km}$  with a standard deviation of 1.3 km for 9 cases, (b) ATSR-2 1.6  $\mu\text{m}$  channel CTHs of  $-0.1\text{ km} \pm 1.9\text{ km}$  for 9 cases and (c) ATSR-2 0.65  $\mu\text{m}$  channel CTHs of  $0.2\text{ km} \pm 2.1\text{ km}$  for 7 cases. When there were height disagreements in the remaining cases, they were the result of ATSR-2 either detecting high clouds that were beyond the detection limit of the radiosonde (in terms of accuracy of the relative humidity measurements or spatial coincidence of the radiosonde with the cloud) or failing to detect high clouds in multiple layer cases. Optically thin clouds above lower level clouds and scattered, broken clouds were the most difficult cloud types to simultaneously detect from both ATSR-2 and radiosonde observations.

#### **4. Comparison between MOS O<sub>2</sub>-A band CTP and ATSR-2-stereo and ground-based CTH**

During the validation campaign from August 1998–March 1999, we identified fourteen MOS scenes over the United Kingdom that occurred within half an hour of an ATSR-2 overpass. Using the O<sub>2</sub>-A band technique (Fischer and Grassl 1991), Preusker *et al.* (2007) converted the MOS radiances into estimates of cloud-top pressure that were subsequently transformed into geopotential heights using ECMWF re-analysis profiles (ERA-15; Gibson *et al.* 1999). Of these fourteen scenes, one was also coincident with 94-GHz radar observations and four were coincident with radiosonde launches from either Aberporth or Hemsby stations. We sampled the MOS- and ATSR-2-derived cloud top heights across the same  $\pm 0.02^\circ$  latitude-longitude boxes centred at Chilbolton, Aberporth and Hemsby as before. A summary of CTHs retrieved from the MOS instrument is presented in tables 1 and 2.

There was only one pass over Chilbolton when MOS O<sub>2</sub>-A band, ATSR-2 and the radar indicated a cloud. On this day (1998-11-27) the CTH differences between the radar, MOS O<sub>2</sub>-A band and ATSR-2 1.6  $\mu\text{m}$  and 0.65  $\mu\text{m}$  channel CTHs were within 1 km, while the ATSR-2 11  $\mu\text{m}$  channel CTH was about 2 km lower than the others.

For the Aberporth and Hemsby comparisons on 1999-01-14 only MOS and the ATSR-2 0.65  $\mu\text{m}$  and 1.6  $\mu\text{m}$  channels detected a cloud with the ATSR-2 0.65  $\mu\text{m}$  channel CTH being higher. For the second case study period (1999-01-23) the MOS CTH was between the ATSR-2 1.6  $\mu\text{m}$  and 0.65  $\mu\text{m}$  channel CTHs, while the ATSR-2 11  $\mu\text{m}$  channel CTH was unrealistically high for mid-winter cirrus. For this case the RS methods detected a cirrus layer at 11 km, also detected by the ATSR-2 1.6  $\mu\text{m}$  channel, but missed by the MOS and ATSR-2 0.65  $\mu\text{m}$  channel retrievals. Furthermore, the standard deviations for ATSR-2 CTHs were generally large compared to the MOS CTH standard deviation, indicating a larger uncertainty in true cloud top height for this case. On 11 February 1999 the RS techniques indicated a multilayer cloud system and MOS CTH referred to the next to highest cloud layer, in agreement with the ATSR-2 0.65  $\mu\text{m}$  channel retrieval. On the last comparison day of 2 March 1999 the RS methods indicated a cloud layer from the surface up to an altitude of 12 km, most likely indicating the presence of a multi-layer cloud system. If multiple cloud layers are present and the upper layers are thin, the increase in photon path length due to multiple scattering between layers will always lead to the MOS O<sub>2</sub>-A band retrievals underestimating the CTH (Preusker *et al.* 2007). For this multi-layer cloud case the MOS O<sub>2</sub>-A band CTH was lower than all of the other retrievals.

There were another four dates when MOS passed over Aberporth or Hemsby near the time of radiosonde launches, so we have in total eight dates to compare the RS and MOS CTH retrievals (table 3, figure 3). We found that for clouds retrieved below 5 km by the RS techniques the MOS CTHs were higher, whereas for clouds with tops above 10 km in the RS approaches MOS had much lower CTHs. For the latter cases we found that on three occasions the MOS CTH was within the highest layer detected by the RS techniques, on one occasion the MOS CTH was close to the CTH of the layer below the highest one detected by the RS techniques, and on two other occasions the MOS CTH was between two RS layers. Overall, in most cases, the MOS approach detected the same layer as the RS methods but failed to pick up the highest levels of the layer. This result was not surprising in the context of our statements above, where we emphasized that MOS CTHs tend to underestimate the true cloud top height in instances of optically thin cloud over lower level clouds. This problem led to the average difference between RS and MOS CTHs of  $4.3 \pm 4.6$  km for all cases. For the 4 cases with an agreement on cloud level the difference was  $2.8 \pm 4.0$  km.

## 5. Comparison between MOS O<sub>2</sub>-A band CTP and ATSR-2 stereo CTH over the British Isles

In addition to the localised comparisons in §4 we also performed a pixel-by-pixel comparison of MOS and ATSR-2 CTH retrievals when scenes from the two instruments overlapped. To this end we re-projected MOS CTHs into the ATSR-2 latitude-longitude grid and compared the retrieved CTHs pixel-by-pixel. This was also performed the other way round (i.e. ATSR-2 projected into MOS grid) which indicated negligible differences caused by resampling. Examples of MOS and ATSR-2 CTH retrievals for 1998-10-10 and 1998-10-29 are illustrated in figures 4

Table 3. MOS O<sub>2</sub>-A band, RS CE96-80%, CE96-60% and WR95 median CTHs and standard deviations over Aberporth and Hemsby. The MOS CTHs were selected within a  $\pm 0.02^\circ$  latitude-longitude box centred on the radiosonde stations. The cloud conditions are derived from the RS cloud boundary retrieval to decide if the situation is single or multiple layers, and from MOS CTHs distributions within the latitude-longitude box to decide if the highest layer is scattered or overcast. When MOS does not detect a high cloud layer in multilayer conditions, either ATSR-2 CTH distributions are used if available or the case is undecided.

Date	Cloud condition	MOS median CTH (km)	CE96-80% CTH (km)	CE96-60% CTH (km)	WR95 CTH (km)	Comments
14 January 1999	Clear, scattered single clouds	$1.8 \pm 0.6$	0.0	0.0	0.0	False positive
26 December 1998	Single overcast mid-level layer	$6.3 \pm 0.1$	2.5	3.8	4.6	MOS CTH > RS CTH
25 December 1998	Multilayer overcast highest layer	$7.7 \pm 0.1$	9.2	10.4	10.5	MOS CTH < RS CTH but same layer
2 March 1999	Single overcast layer	$4.9 \pm 0.2$	11.9	12.0	12.3	
23 January 1999	Multilayer overcast highest layer	$7.3 \pm 0.1$	10.6	11.2	11.2	
11 February 1999	Multilayer, scattered	$3.9 \pm 0.0$	3.4	12.3	11.8	MOS CTH < RS CTH but layer below highest
12 March 1999	Multilayer	$2.5 \pm 0.2$	10.6	11.8	10.5	MOS CTH between 2 RS layers
31 March 1999	Multilayer	$4.0 \pm 1.6$	1.1	11.6	11.7	

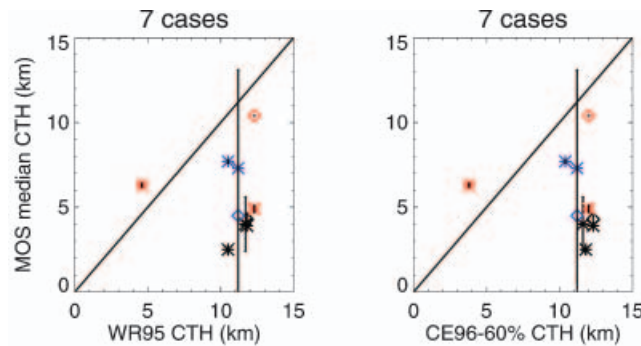


Figure 3. Comparison between MOS O<sub>2</sub>-A band, WR95 and CE96-60% median CTHs over Aberporth and Hemsby(\*). When ATSR-2 CTHs are available (3 dates), the ATSR-2 0.65  $\mu$ m channel CTHs are plotted against corresponding CE96-60% and WR95 CTHs (diamonds). Black shows high thin or scattered clouds over lower level clouds, blue refers to multilayer with highest levels overcast, red refers to single level overcast clouds.

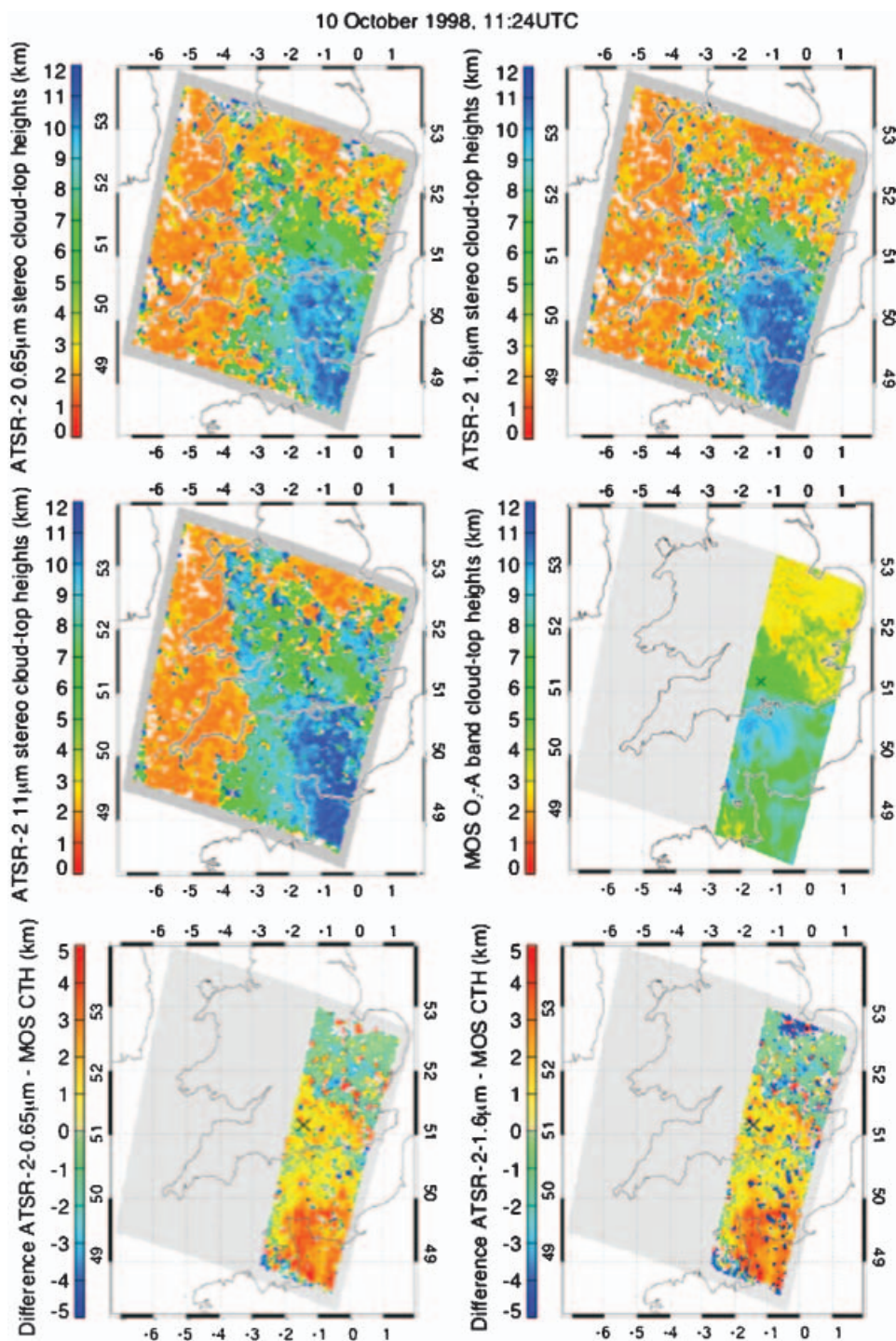


Figure 4. ATSR-2 0.65  $\mu\text{m}$  channel (top left), ATSR-2 1.6  $\mu\text{m}$  channel (top right) and ATSR-2 11  $\mu\text{m}$  channel (centre left) stereo and MOS O<sub>2</sub>-A band (centre right) CTHs for 10 October 1998. Difference between ATSR-2 and MOS CTHs for ATSR-2 0.65  $\mu\text{m}$  (lower left) and 1.6  $\mu\text{m}$  (lower right) channels.

and 5. As figure 5 suggests, the MOS and ATSR-2 mean CTHs were fairly consistent for these two scenes. However, for high clouds the ATSR-2 11  $\mu\text{m}$  channel CTHs were generally higher than the MOS CTHs, whereas for low clouds the ATSR-2 11  $\mu\text{m}$  channel CTHs were generally lower. For both scenes large CTH differences between the two approaches were noticeable. One potential cause of these differences was that the MOS CTH retrievals tended to be much smoother than the ATSR-2 retrievals, as there are large variations in the stereo-derived CTHs with potentially significant contributions of noise (figure 4).

Area-based comparisons for four different scenes occurring on 2 September 1998, 12 September 1998, 10 October 1998 and 27 November 1998 are illustrated in figure 6, where we plot the relative frequency of occurrence of CTH in the scene that results from each retrieval. Again, in multiple layer cloud cases the MOS CTH retrieval either missed the highest CTH (2 September 1998 and 12 September 1998) or underestimated the CTH of clouds above 7 km (10 October 1998). On 10 October 1998 the lowest clouds were detected at a higher level by MOS CTH compared to the ATSR-2 stereo CTHs. For the last scene (27 November 1998), which contained mainly low- or mid-level clouds, the agreement between all retrievals was high, except for the ATSR-2 11  $\mu\text{m}$  channel brightness temperature retrieval.

## 6. Discussion and conclusions

We compared stereo-derived cloud top heights from Along Track Scanning Radiometer 2 (ATSR-2) 0.65  $\mu\text{m}$ , 1.6  $\mu\text{m}$  and 11  $\mu\text{m}$  channel observations over the United Kingdom from September 1998–March 1999 with cloud top heights derived from radar, radiosondes and the Modular Optoelectronic Scanner (MOS) instrument onboard the IRS-P3 satellite. The comparison between ATSR-2 and ground-based CTH retrievals was complicated, as it involved comparing instantaneous, large spatial coverage satellite data with point measurements that covered long time periods. The main problem in our comparisons was the presence of broken clouds, which were not always detected by ground-based instruments, e.g., the Chilbolton 94-GHz radar, but were present within the ATSR-2 stereo scenes.

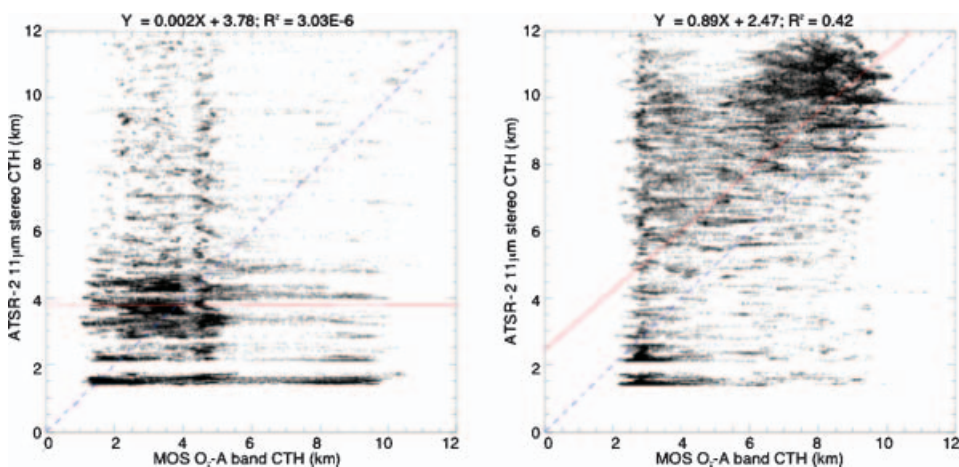


Figure 5. Pixel-by-pixel comparison of ATSR-2 11  $\mu\text{m}$  channel stereo and MOS O<sub>2</sub>-A band CTHs. *Left image:* 29 October 1998, mainly low clouds. *Right image:* 10 October 1998, high clouds.

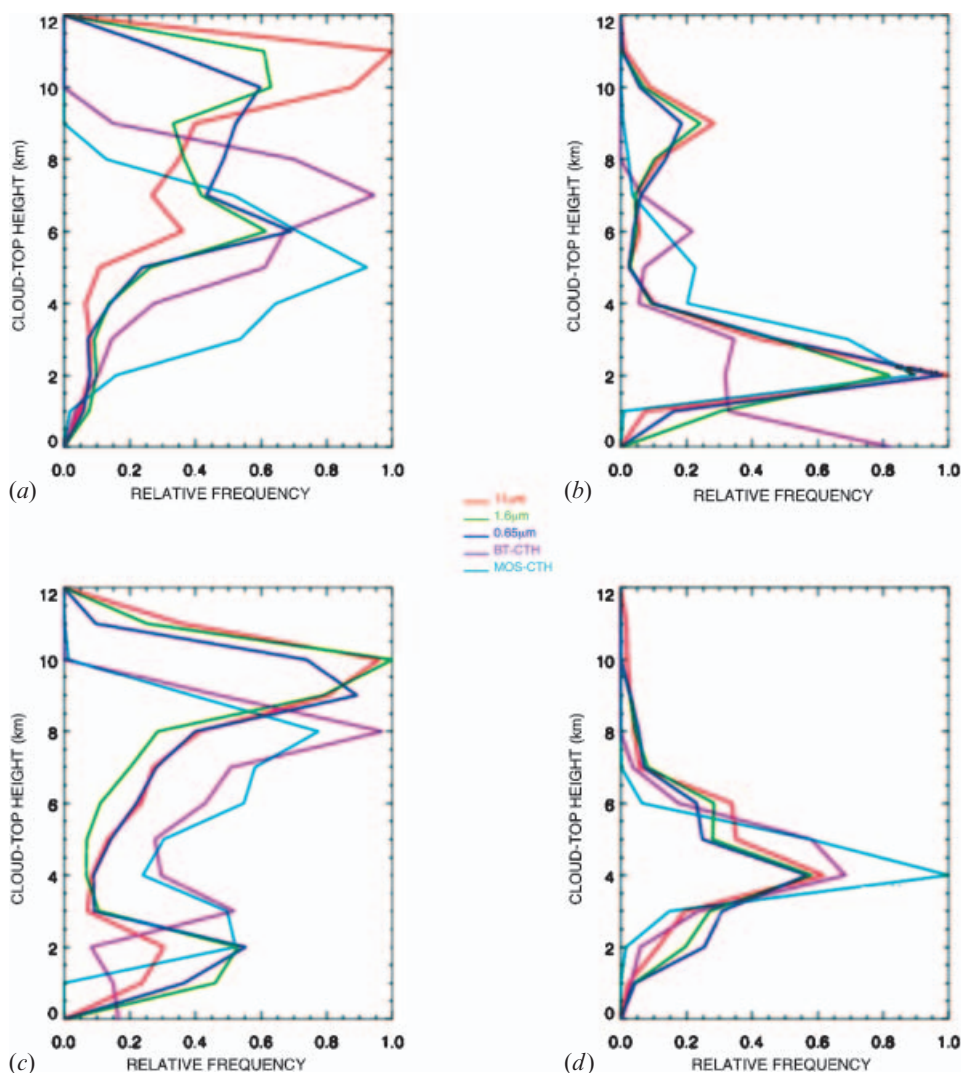


Figure 6. Area-based comparison of CTHs using several different techniques for four dates: ATSR-2 stereo CTH for three channels, MOS O<sub>2</sub>-A band CTH and CTH obtained from ATSR-2 nadir 11  $\mu\text{m}$  brightness temperatures transformed into heights using ECMWF profiles (BT-CTH). (a) 2 September 1998, illustrating poor agreement between all techniques, including ATSR-2 stereo retrievals at different wavelengths. (b) 12 September 1998, illustrating good agreement between MOS O<sub>2</sub>-A band CTH and ATSR-2 stereo techniques. (c) 10 October 1998, illustrating good agreement between ATSR-2 BT-CTH and MOS O<sub>2</sub>-A band CTH. (d) 27 November 1998, illustrating good agreement between all techniques.

Overall, the agreements between the ATSR-2 and 94-GHz radar cloud top height retrievals were within the  $\pm 1$  km theoretical limits expected of the ATSR-2 0.65  $\mu\text{m}$  and 1.6  $\mu\text{m}$  channel retrievals in more than half of the cases that we examined. The differences were larger for the ATSR-2 11  $\mu\text{m}$  channel CTHs, although within 2 km. At high altitudes the ATSR-2 stereo method gave consistently higher CTHs than radar, which was not surprising given that the radar sensitivity decreases as the

inverse square of range, and that smaller particles in these high clouds can make their detection by radar problematic. At altitudes below about 6 km the 94-GHz radar CTHs were generally higher than those retrieved from the ATSR-2 stereo method.

The comparisons with radiosonde profiles also presented problems, especially the spatial collocation of the radiosonde measurements relative to the ground- and satellite-based observations. Notwithstanding the drift of radiosondes outside of the latitude-longitude box centred on the station of interest, radiosondes travelling through clear areas between clouds in broken cloud situations, and general problems using radiosondes to identify cloud layers, more than half the case study periods showed similarities between the radiosonde and ATSR-2 CTH retrievals. The differences in CTH for these cases were usually less than 2 km, which was not unexpected as ATSR-2 stereo cloud top height retrieval accuracy can range from 1 km up to 4 km in the presence of strong winds (Seiz *et al.* 2007).

Overall, we found that the ATSR-2 11  $\mu\text{m}$  channel was much more efficient at detecting high clouds in multilayer cloud conditions. During these conditions, the ATSR-2 0.65  $\mu\text{m}$  channel CTHs tended to be assigned to the top of a lower layer and the ATSR-2 1.6  $\mu\text{m}$  channel CTHs tended to miss clouds altogether. These results suggested that through the use of a combined ATSR-2 11  $\mu\text{m}$  and 0.65  $\mu\text{m}$ , or 1.6  $\mu\text{m}$ , channel retrieval, multiple cloud layers could be detected when the upper cloud layer is thin.

We compared radar, ATSR-2 stereo and MOS O<sub>2</sub>-A band cloud top height retrievals for the one scene that was available over the duration of the campaign. We found that for low clouds the MOS CTHs were lower than the radar CTH and the ATSR-2 1.6  $\mu\text{m}$  and 0.65  $\mu\text{m}$  channel CTH retrievals, but higher than the ATSR-2 11  $\mu\text{m}$  channel CTH retrievals. This result, combined with the comparison with ground-based retrievals, suggests that the ATSR-2 11  $\mu\text{m}$  channel may not be suitable for low cloud CTH assignments because of lack of contrast between the two ATSR-2 views at this wavelength in the case of opaque clouds. Additionally, we identified the ATSR-2 stereo matchers occasionally matching ground pixels, resulting in a reduction in ATSR-2-derived mean CTH as one possible source of this bias.

A comparison between ATSR-2, MOS and radiosonde CTH retrievals showed that, in the presence of multi-layered cloud systems containing high thin clouds, the MOS CTHs were not reliable, as the MOS retrieval was not sensitive to high thin clouds and underestimated the cloud top heights. This feature of the MOS retrieval was not unexpected, as information from a single O<sub>2</sub>-A band absorption channel does not contain enough information for the discrimination of multi-layer clouds. Another comparison between ATSR-2 and MOS CTH retrievals, which took into account the spatial distribution of the retrievals, revealed that the mean values produced by all three techniques, i.e., stereo, brightness temperature and oxygen absorption, agreed quite well, although the ATSR-2 stereo CTHs showed a higher noise level with more variability.

This first attempt to estimate the accuracy of ATSR-2 stereo heights showed that, overall, the retrieval scheme was performing adequately with some indication that high clouds were more likely to be detected with the ATSR-2 11  $\mu\text{m}$  channel than with the other two ATSR-2 channels. The apparent enhanced sensitivity of the ATSR-2 11  $\mu\text{m}$  channel will be investigated further as a way to discriminate between low and high clouds in multi-layer cloud cases when used in conjunction with the other two ATSR-2 channels that were used in this study.

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